Bremsstrahlung of 350–450 MeV protons as a tool to study NN interaction off-shell*

N.A. Khokhlov[a], V.A. Knyr[a], V.G. Neudatchin[b] and Andrey M. Shirokov[b]†

[a]Khabarovsk State Technical University, Khabarovsk 680035, Russia

[b]Institute for Nuclear Physics, Moscow State University, Moscow 119899, Russia

The $pp \to pp\gamma$ bremsstrahlung cross section is calculated within the method of coordinate space representation. It is shown that in the beam energy range of 350–450 MeV a deep attractive NN-potential with forbidden states (Moscow potential) and realistic meson exchange potentials (MEP) give rise to the cross sections that differ essentially in shape: the cross sections nearly coincide in the minima but differ by a factor of 5 approximately in the maxima. Therefore, the $pp \to pp\gamma$ reaction at energies ∼350–450 Mev can be used to study NN interaction off-shell and to discriminate experimentally between MEP and Moscow potential.

The most popular of the NN interactions today are meson exchange potentials (MEP). The central component of the NN interaction within the MEP model has a short-range repulsive core of the radius $r_c \simeq 0.5$–0.6 fm and is attractive at larger distances. Modern ME potentials (Reid, Bonn, Paris, Argonne, Nijmegen, etc.) are carefully fitted to the existing deuteron and NN scattering data up to the laboratory energies of ∼500 MeV and higher. However, these data involve only the on-shell properties of the interaction. The off-shell properties of the interaction are prominent in the binding energies of few-body systems. It is well-known that ME potentials underbind the trinucleon and light nuclei, and this problem cannot be solved within the MEP model by allowing for realistic three-body forces [1].

An alternative to the MEP model is the model of a deep attractive NN potential (the so-called Moscow potential, MP) [2,3]. MP supports additional deeply-bound states in S and P waves which are treated as forbidden states. The first excited state reproduces the deuteron properties, the scattering observables are also well-described by the latest version of MP [3]. At short distances where the MEP model wave function is suppressed by the repulsive core, the MP wave function has an additional node in S and P waves that may be interpreted as a manifestation of the 6-quark configurations $s^4p^2[42]_X[42]_{CS}$ and $s^3p^3[33]_X[51]_{CS}$ in S and P waves, respectively.

MP and ME potentials are nearly equivalent on-shell at low and moderate energies but differ essentially off-shell. However, both MEP and MP underbind ^{3}H. So, neither ME

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†E-mail: shirokov@anna19.npi.msu.su

nor Moscow potential model is favored by the few-body verification of the NN interaction off-shell. MEP model is based on the well-developed ideas of meson exchange. At the same time, recent microscopic studies of NN interaction in a chiral constituent quark model [4] support the idea of the existence of the node of the NN wave function at short distances. However, the amplitude of the oscillation of the wave function at short range is suppressed as compared with the MP wave function. So, MP and MEP can be treated as modern limiting models of the interaction of real nucleons built of quarks.

Theoretical studies of $pp \to pp\gamma$ reaction have been performed in a number of papers (see, e.g., [5–14] and references therein). As it is concluded in a recent paper of Jäde et al [14], the result of numerous calculations of various authors is very discouraging from the point of view of using pp bremsstrahlung as a comparative test of NN potentials: the difference in the $pp \to pp\gamma$ cross sections calculated with different NN potentials is too small to be measured experimentally. There are two reasons for this disappointing result. First, as a rule only NN potentials based on the ideas of ME have been used in the calculations, and the $pp \to pp\gamma$ results are just the manifestation of the fact that there is nearly no difference between various ME potentials. Next, usually the theoretical investigations have been restricted to the beam energies not exceeding 280 MeV that have been studied experimentally [5]. However, as we shall show below, the $pp \to pp\gamma$ reaction at energies 350–450 MeV can be used to discriminate between phase equivalent NN potentials that differ essentially off-shell like MEP and MP. We suppose that our result have a more general meaning showing that the detection of hard photons accompanying pp scattering at energies of $\sim$400 MeV can be used to examine the off-shell properties of NN interaction and to test various models of NN interaction, e.g., the ones explicitly allowing for the quark degrees of freedom. Note, that the experimental studies in this energy interval are planned for the nearest future and some of them have been already started [15].

We study the coplanar $pp \to pp\gamma$ reaction using the formalism of the coordinate space representation described in detail elsewhere [16]. The formalism makes it possible to avoid various approximations that are used within the more conventional formalism of the momentum space representation employed in Refs. [6,8–14].

Meson exchange currents are not allowed for in our calculations. The contribution of the meson exchange currents to the $pp \to pp\gamma$ cross section has been discussed in detail in Refs. [11–13]. Meson exchange contribution is inessential at 280 MeV but increases with energy. It is small for the emission of soft photons, increases with the photon energy, and decreases in the case of emission of the photons of the maximal possible energy. At the same time, the off-shell differences between the potential are most prominent in the latter case when the energy of relative motion of protons in the final state is small. This corresponds to the kinematics when the angle between the protons in the final state is small enough. So, the detection of protons at small angles is favorable from the point of view of studying NN interaction off-shell while larger angles are more preferable for studying meson exchange contributions.

Our results for ME Paris potential [17], hard-core Hamada–Johnston potential [18] and MP [3] (see also [16] for improvement of MP higher partial waves) are presented on the figure. The predictions obtained with all above potentials for the $pp \to pp\gamma$ differential cross sections at the incident proton energy $\epsilon = 280$ MeV are very similar and describe

well the experimental data of Ref. [5]. The same conclusion has been derived previously by Fearing [8] who also involved MP in the analysis of the $pp \to pp\gamma$ reaction cross section.

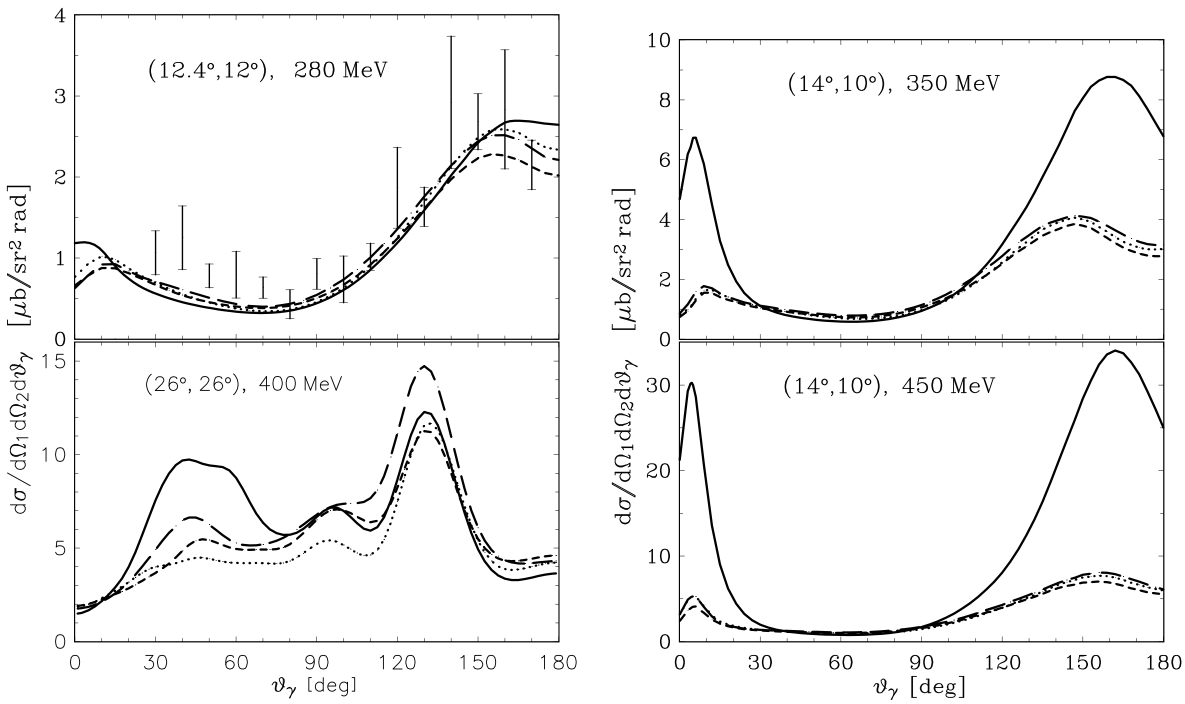

Figure 1. $pp \to pp\gamma$ cross section. The angles of the final protons are Θ_1 and Θ_2 and the beam energy ϵ are shown at each panel. The results of calculations with MP, super-symmetry partner of MP, Paris potential and Hamada–Johnston potential are plotted by solid, dotted, long-dashed and short-dashed lines, respectively. Experimental data are taken from [5].

However, the situation changes drastically if the beam energy ϵ is increased up to 350 or 450 MeV. As is seen from the figure, the cross section obtained with MP has well-pronounced peaks for the emission of forward and backward photons that correspond to the maxima of the photon energies in the C.M.S.; the respective maxima obtained with Paris and Hamada–Johnston potentials are much less pronounced. The maximal values of the cross section for MP and Paris or Hamada–Johnston potentials differ by a factor of several times while the cross section for $30^\circ < \Theta_\gamma < 90^\circ$ is the same for all potentials. Therefore, to discriminate experimentally between MP and MEP in the $pp \to pp\gamma$ reaction at the energy range of 350—450 MeV, one can study the Θ_γ-dependence only without absolute normalization of the cross section. Note, that difference between MEP and MP predictions is larger than the meson exchange contribution even if it is calculated at larger energies $\epsilon = 550$ MeV and larger proton angles (see [12]).

We have calculated also the MP super-symmetry partner [19] that is exactly phase-equivalent to MP but supports the wave function without the additional node like Paris potential. It is seen from the figure that the results obtained with the MP super-symmetry partner, Paris and Hamada–Johnston potentials are nearly the same and differ essentially

from the ones obtained with MP. Thus, the difference between MP and MEP predictions for $pp \to pp\gamma$ reaction at energies of 350—450 MeV arise from the difference of the wave functions at short range. The difference is enhanced when the emitted photon has the maximal possible C.M.S. energy for the given energy of the proton beam. Therefore, the enhancement corresponds to the minimal C.M.S. energy of the relative motion of the final protons. This kinematics emphases the role of the S and P components in the NN relative motion in the final state which differ essentially at short range for MP and MEP. The results of calculations for $\epsilon = 400$ MeV correspond to the kinematical conditions of the experiment started in Osaka [15]. Unfortunately, the angle between final protons in this experiment is large ($26^\circ + 26^\circ = 52^\circ$) and the off-shell differences between the potential are less pronounced and are comparable with the meson exchange contributions [12].

Summarizing, we have shown that the predictions for $pp \to pp\gamma$ reaction at the beam energies of 350—450 MeV obtained with the deep attractive Moscow potential differ essentially from the ones obtained with ME Paris and hard-core Hamada–Johnston potentials. So, the proton-proton bremsstrahlung at energies of ∼400 MeV can be used to study NN interaction off-shell and to discriminate between Moscow and ME potential models.

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